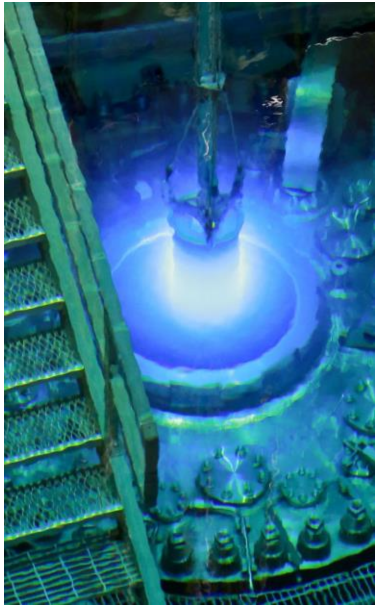
EUROPEAN SPALLATION SOURCE

What facilities (*will*) exist to do ***fundamental cross-frontier BSM searches*** with the humble neutron? Consider the COHERENT approach…

Oak Ridge National Laboratory



Searches for Transformations of Neutrons to Sterile Neutrons and Antineutrons at ORNL and ESS

by Joshua Barrow, jbarrow3@vols.utk.edu

Snowmass 2021 Rare Processes and Precision Frontier

Dark Sectors Topical Group

October 2nd, 2020

Please see the associated Letter of Interest, and references therein

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URA UNIVERSITIES RESEARCH ASSOCIATION

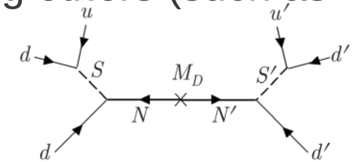
This presentation is based upon work that is supported by the Visiting Scholars Award Program of the Universities Research Association. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the Universities Research Association, Inc.

BSM Interactions Should be Tested Using the Neutron

Physics Motivations *Including and Beyond* Dark Matter

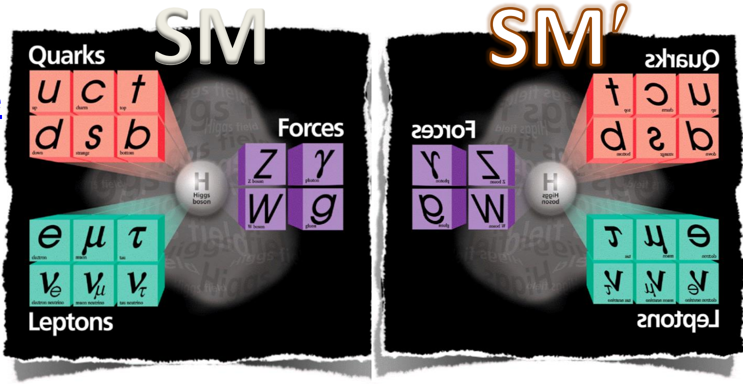
New models propose novel low-mass DM (Foot) particles and interactions and call out to be experimentally constrained and/or eliminated

- Can map onto rich low energy phenomenology with neutrons in mind—Cosmic Visions 2017
- Searches for $\mathcal{B}$-violating oscillatory behavior (Berezhiani) with neutral particles (***neutrons underexplored***) is one of many important venues to consider among others (such as *fundamental symmetries*)



$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}'_{SM} + \boldsymbol{\mathcal{L}_{mix}}$$

- **$n \to \bar{n}$ transformations are strongly motivated:** $|\phi_n\rangle = \begin{vmatrix} n \\ \bar{n} \end{vmatrix}\rangle$
  - $|\Delta\mathcal{B}| = 2$: free and bound oscillations are possible, **ties to baryogenesis**
- **Can similarly think of $n \to n'$ conversion:** $|\phi_n\rangle = \begin{vmatrix} n \\ n' \end{vmatrix}\rangle$
  - $|\Delta\mathcal{B}| = 1?$: **possible connections to DM and the n lifetime puzzle**
- Can even consider larger systems: $|\phi_n\rangle = \begin{vmatrix} n \\ n' \\ \bar{n}' \\ \bar{n} \end{vmatrix}\rangle$
  - Possible connections to cobaryogenesis (Berezhiani)



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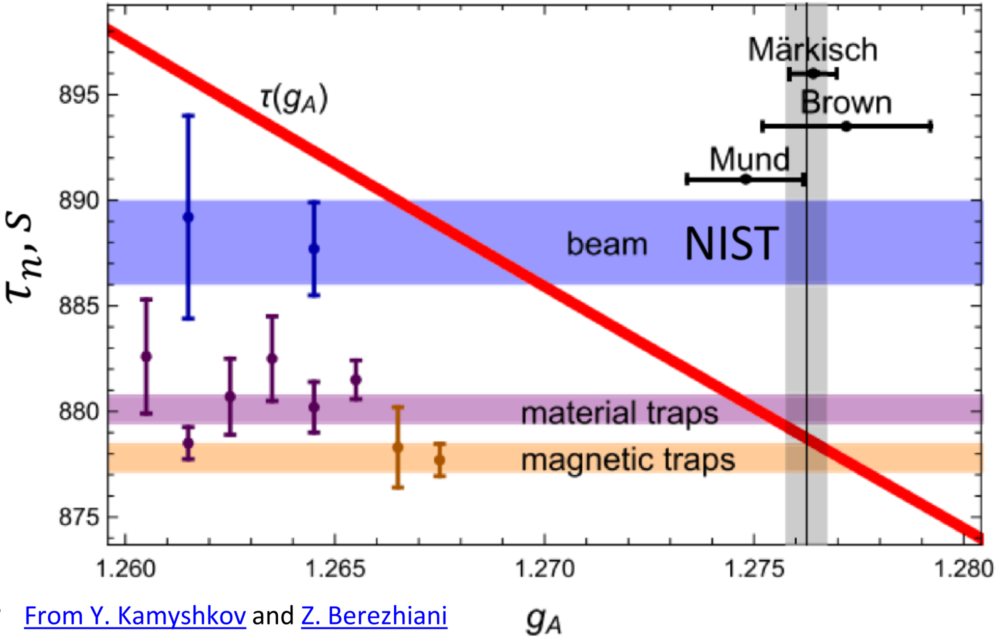
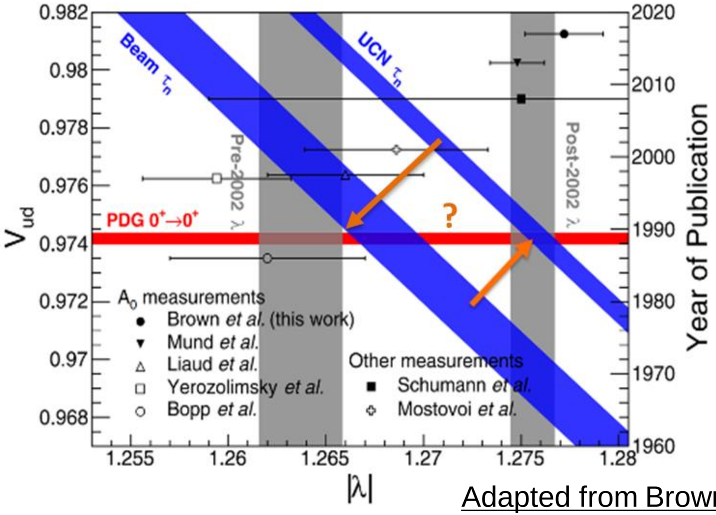
We Can Pursue DM and the Neutron Lifetime “Puzzle” *Together*



From Y. Kamyshkov and Z. Berezhiani

Disparities between beam and bottle n-lifetime measurements highlight persistent, *growing* $\sim 4\sigma$ tensions within SM physics

- Could interactions with a dark sector contribute to these disparities?
  - Can we use existing and future intense neutron sources to search for new physics?



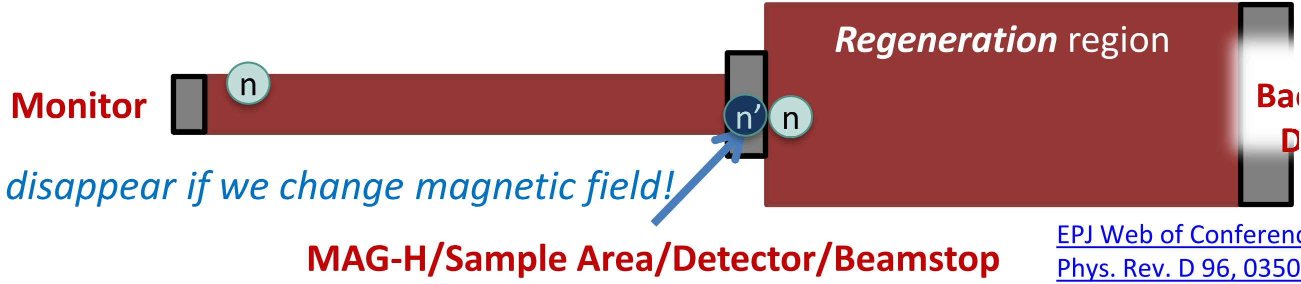
Adapted from Brown et al.

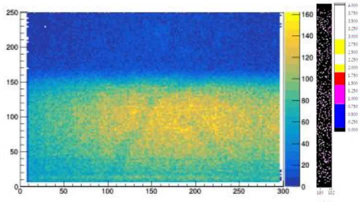
Understanding the potential BSM sources of these tensions creates high impact science, and can conduct great synergy between nuclear, particle, and BSM physics communities

Adapted from L. Broussard

Search Principles for $n \rightarrow n'$ with Cold Neutrons

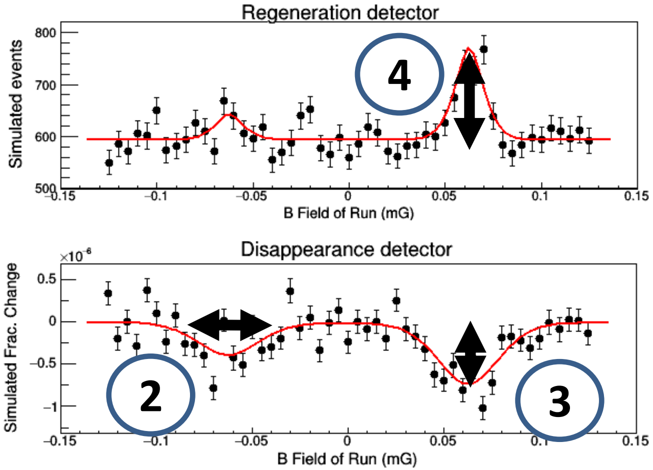
From *existing* SNS and HFIR instrument facilities and beyond





EPJ Web of Conferences 219, 07002 (2019)
Phys. Rev. D 96, 035039

1 $$P(n \rightarrow n' \rightarrow n) \propto \left(\frac{t_{Dis}}{\tau}\right)^2 \left(\frac{t_{Reg}}{\tau}\right)^2$$



1. High neutron flux with **long, large area guides**
2. **Magnetic field uniformity *and control***
3. **Precise monitoring** of changes in **transmission**
4. ***Regeneration***: large area, low background detector

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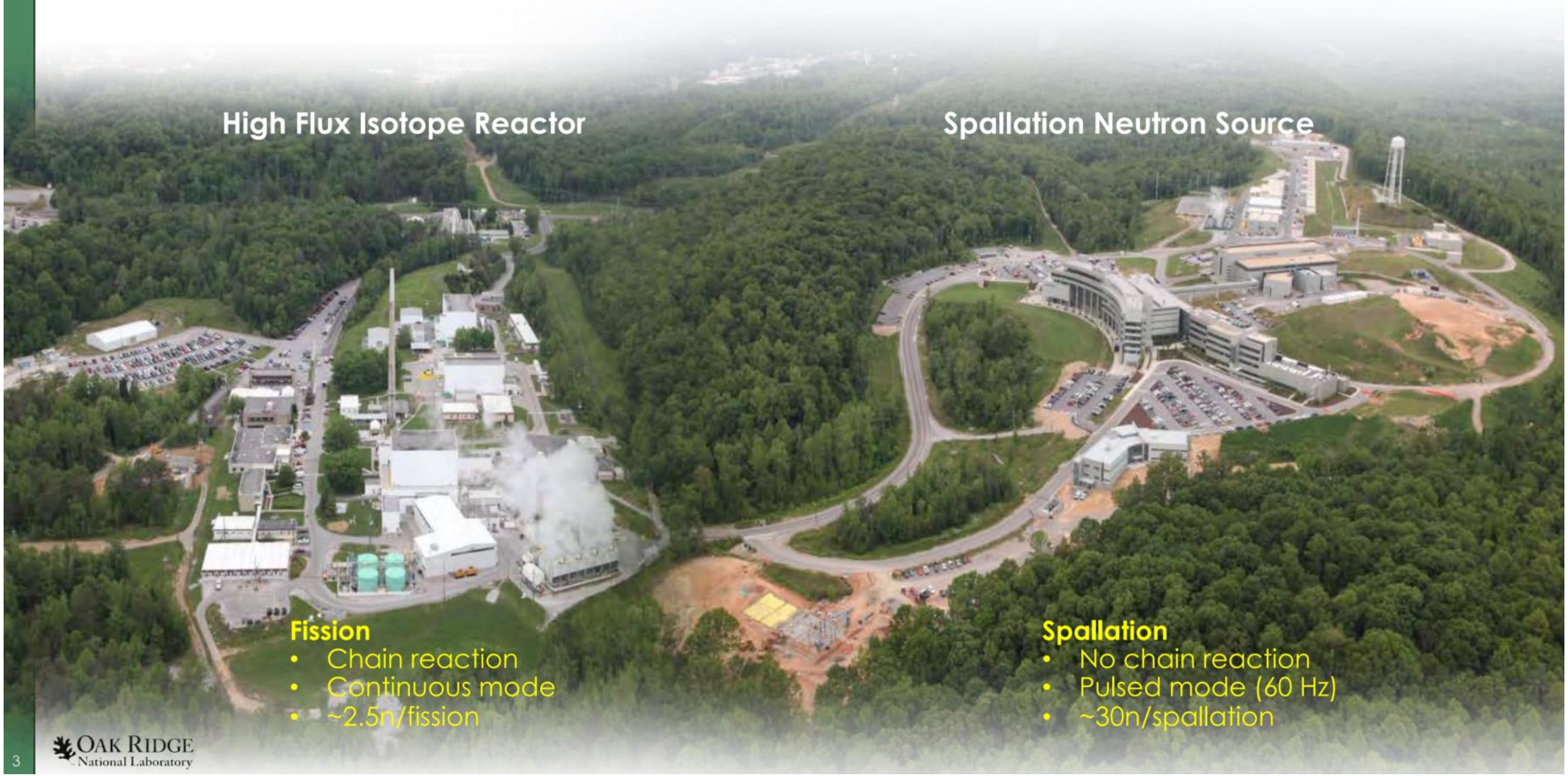
From [Marcel Demarteau]

ORNL operates two world-class neutron facilities

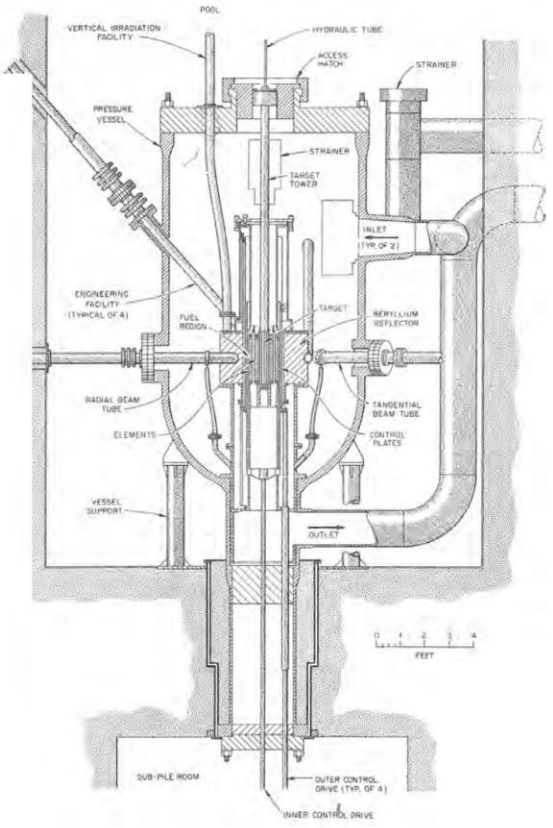


From Marcel Demarteau

HFIR Upgrade: Pressure Vessel Replacement to provide significant enhancements

“A dedicated fundamental physics laboratory at an upgraded HFIR or a new reactor could have a transformative impact on the field of fundamental physics and the synergistic and collaborative efforts of scientists within the [DOE] Office of Science”

-BESAC report



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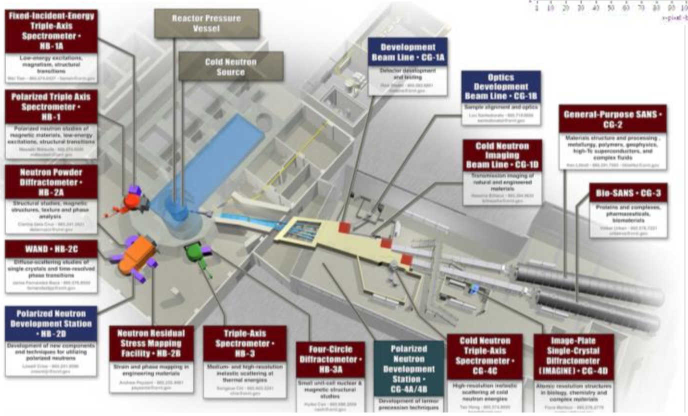
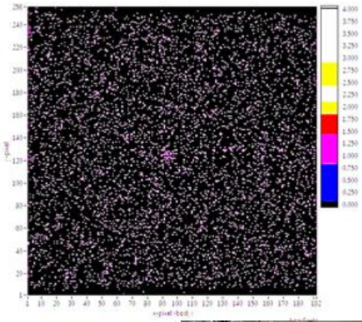
The Fundamental Physics Community Should Utilize Existing Precision Facilities

New Experiments at the High Flux Isotope Reactor (HFIR) GP-SANS Beamline

Basic Energy Science funded facilities are available for robust fundamental physics searches through active User Programs

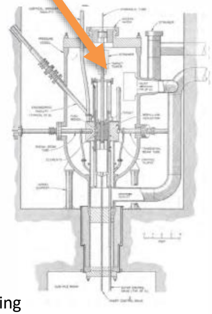
- 85 MW reactor with large, low background detectors ($\sim 3\ n/s$) downrange
- Highest flux reactor-based source of neutrons for research in the US
  - $\mathbf{10^{10}\frac{n}{s}}$ **downbeam**, long flight paths
- **Upgrade coming *beyond* beryllium changeout!**
  - New! 100 MW!
  - Here to stay!





Long-term vision: A future pressure vessel replacement could provide an opportunity for significant enhancements

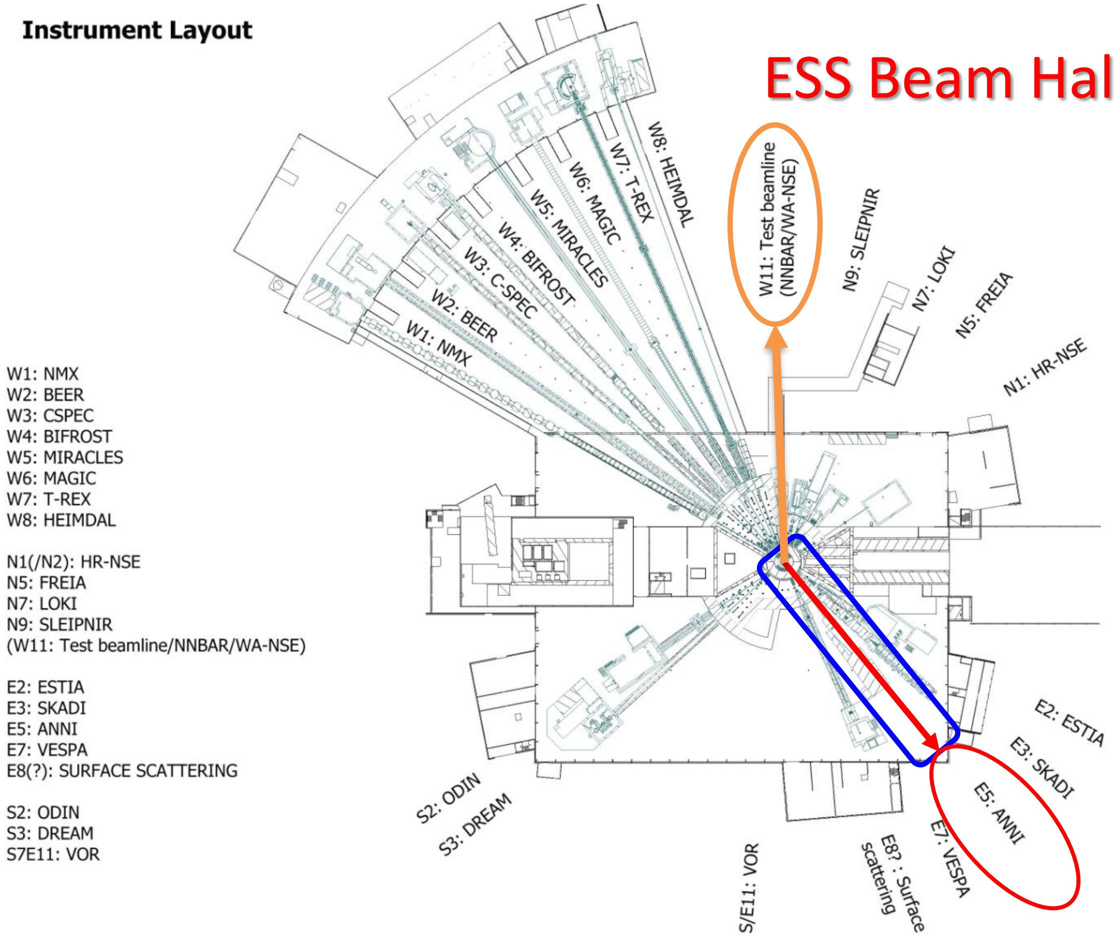
- **New pressure vessel:**
  - Operating at 100 MW (instead of 85 MW)
  - Extending life of HFIR by 50 years
- **D_2O reflector:**
  - Significant performance gain
- **Second guide hall at HB-2:**
  - ~10 instruments at much lower background
- **Upgraded cold source:**
  - ~50% higher brightness for neutron at $\lambda > 2$ Å



OAK RIDGE National Laboratory

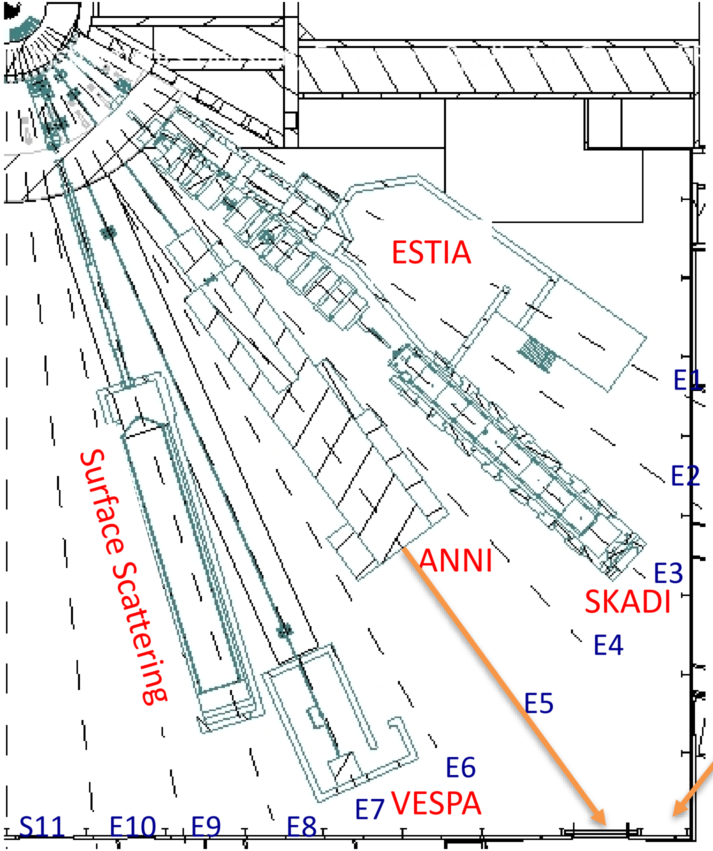
Presented at Joint ACNS 2020 SHUG Meeting

ESS Beam Hall



Provisions for ANNI/HIBEAM

Note that all $n \to n'$ experiments can begin without operation of the full beam intensity, and so we can start (and finish) *before* others who require such intensity



Plenty of space moving toward the corner of the building

$\sim 10^{10} n/s$, even without n reflectors!

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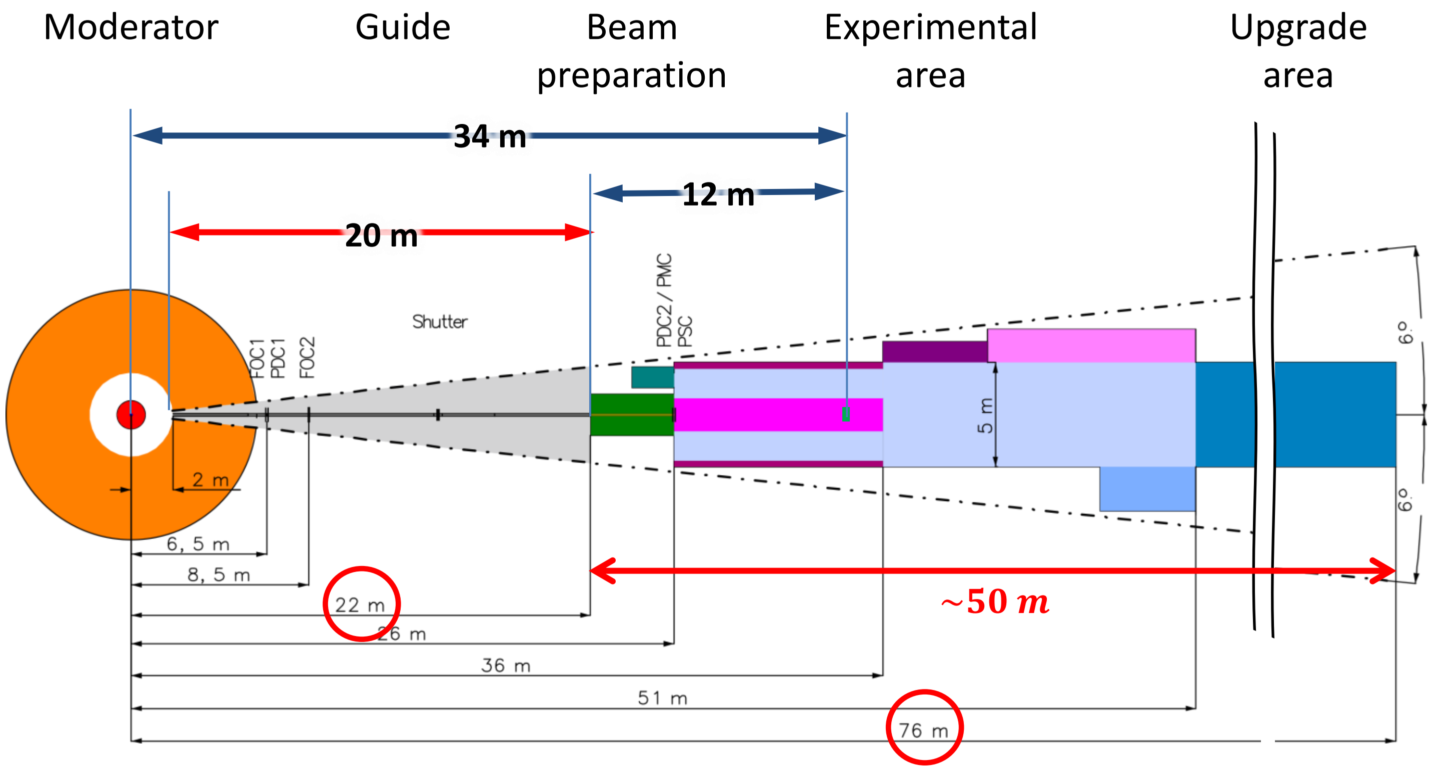
ANNI/HIBEAM – Overview

Adapted from Torsten Soldner



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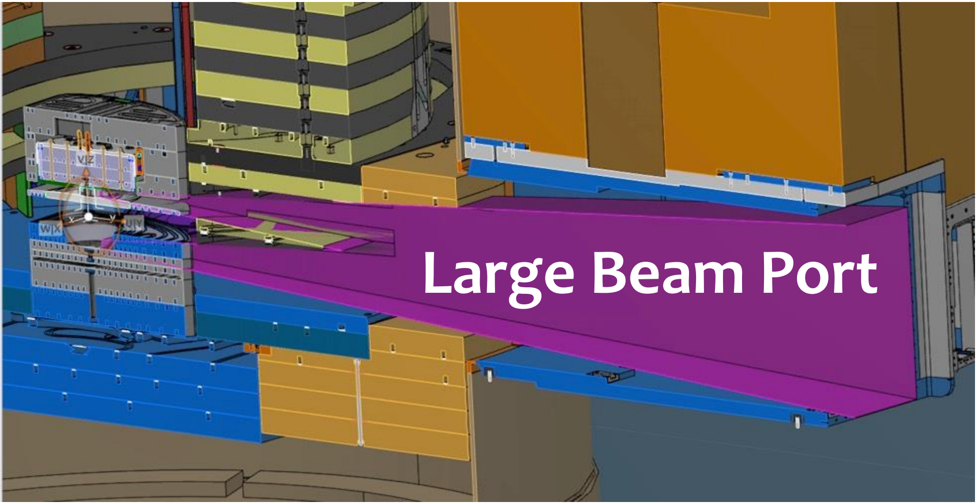
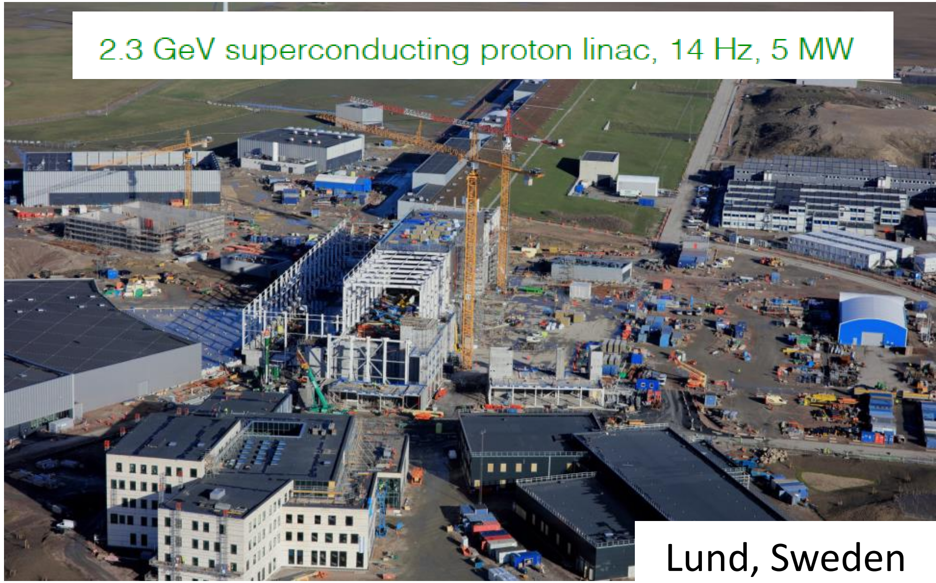
NNBAR at ESS LBP

Direct Baryon Number Violation Searches on the Horizon Using Future Accelerator-Based Spallation Neutron Facility





"The Large Beam Port is an opportunity to broaden the ESS mission"

Rikard Linander, Head of the ESS Target Division

ESS Status: Construction 70% Completed
Beam On Target: 2022
Start of the User Program: 2023
End of Construction for the first 15 instruments: 2025

Good $n \to n'$ multiphysics can be done as a part of R&D preparation for $n \to \bar{n}$ experiments

New high-sensitivity searches for neutrons converting into antineutrons and/or sterile neutrons at the European Spallation Source

A. Addazi[h,at], K. Anderson[aq], S. Ansell[bm], K. S. Babu[az], J. Barrow[w], D. V. Baxter[d,e,f], P. M. Bentley[ac], Z. Berezhiani[b,l], R. Bevilacqua[ac], R. Biondi[b], C. Bohm[ba], G. Brooijmans[an], L. J. Broussard[aq], B. Dev[ay], C. Crawford[z], A. D. Dolgov[ai,ao], K. Dunne[ba], P Fierlinger[o], M. R. Fitzsimmons[w], A. Fomin[n], M. Frost[aq], S. Gardiner[c], S. Gardner[z], A. Galindo-Uribarri[aq], P. Geltenbort[p], S. Girmohanta[bb], E. Golubeva[ah], G. L. Greene[w], T. Greenshaw[aa], V. Gudkov[k], R. Hall-Wilton[ac], L. Heilbronn[x], J. Herrero-Garcia[be], G. Ichikawa[bf], T. M. Ito[ab], E. Iverson[aq], T. Johansson[bg], L. Jönsson[ad], Y-J. Jwa[an], Y. Kamyshkov[w], K. Kanaki[ac], E. Kearns[g], B. Kerbikov[al,aj,ak], M. Kitaguchi[ap], T. Kittelmann[ac], E. Klinkby[ae], A. Kobakhidze[bl], L. W. Koerner[s], B. Kopeliovich[bi], A. Kozela[y], V. Kudryavtsev[ax], A. Kupsc[bg], Y. Lee[ac], M. Lindroos[ac], J. Makkinje[an], J. I. Marquez[ac], B. Meirose[ba,ad], T. M. Miller[ac], D. Milstead[ba,*], R. N. Mohapatra[j], T. Morishima[ap], G. Muhrer[ac], H. P. Mumm[m], K. Nagamoto[ap], F. Nesti[l], V. V. Nesvizhevsky[p], T. Nilsson[r], A. Oskarsson[ad], E. Paryev[ah], R. W. Pattie, Jr.[t], S. Penttilä[aq], Y. N. Pokotilovski[am], I. Potashnikova[bi], C. Redding[x], J-M. Richard[bj], D. Ries[af], E. Rinaldi[au,bc], N. Rossi[b], A. Ruggles[x], B. Rybolt[u], V. Santoro[ac], U. Sarkar[v], A. Saunders[ab], G. Senjanovic[bd,bn], A. P. Serebrov[n], H. M. Shimizu[ap], R. Shrock[bb], S. Silverstein[ba], D. Silvermyr[ad], W. M. Snow[d,e,f], A. Takibayev[ac], I. Tkachev[ah], L. Townsend[x], A. Tureanu[q], L. Varriano[i], A. Vainshtein[ag,av], J. de Vries[a,bh], R. Woracek[ac], Y. Yamagata[bk], A. R. Young[as], L. Zanini[ac], Z. Zhang[ar], O. Zimmer[p]

[ESS HIBEAM/NNBAR program white-paper]

Future Free n Beam Searches at the European Spallation Source

International collaboration is growing around future European Spallation Source beamlines and neutron oscillation experiments

- Collectively rebuild expertise through small scale experiments focused on $n \to n'$

White paper on European opportunities for free $n \to n'$ and $n \to \bar{n}$ [on the arXiv]

- Intended for Physics Reports
  - Snowmass contribution with broader context to follow
- Will pursue a similar, complete study of currently available intense sources here in the US
  - Other BSM searches with neutrons (EDM, etc)?

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Overarching Summary

- **Neutron transformation physics at existing and future intense sources offers a powerful portal onto DM, baryogenesis, and BSM physics**
- The development of an **international collaboration** (ESS HIBEAM and NNBAR) **continues**
  - Will include key **R&D work at ORNL HFIR/SNS**, with full **experiments ongoing**
  - ESS HIBEAM/NNBAR program white-paper is complete
- **Small, cheap $n \rightarrow n'$ experiments, with little to no impact on larger user programs, allow for fast-tracked science with key R&D potentials for larger-scale $n \rightarrow \bar{n}$ searches**
  - If interested in this physics, see our ACFI workshop!

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Work to be completed by Summer 2021

- Calibration of HFIR detector with white beam has been completed with magnet installed, analysis underway!
  - Currently planned HFIR run is upcoming very soon!
  - Analysis of previous SNS search ongoing
  - Analysis of HFIR data forthcoming
  - Publication(s) to follow for various $n \to n'$ style searches
- Active international collaborators are also involved in…
  - NNBAR/HIBEAM with $n \to n'$, $n \to n' \to \bar{n}$, and $n \to \bar{n}$ in mind
  - HighNESS project is now designing an optimum lower moderator for NNBAR
    - Direct outcome: Full NNBAR conceptual design report to be completed in < 3 years
    - Critical to understand all R&D components $n \to n'$ searches at HFIR/SNS and HIBEAM/ANNI can jointly offer us
  - Greater US-based collaboration and support is necessary

Joint Efforts and Snowmass Outcomes

- Neutron sources are underutilized for fundamental physics programs
  - BES has begun greater accommodations for particle physics searches
    - We should endorse and follow these opportunities
  - Fast, cheap, small experiments can produce high-impact science
  - Searches for rich dark sectors and BNV are only the tip of the iceberg!
- Actively looking for detector/instrumentation collaborators
  - Neutron detectors, annihilation detectors, fast electronics, analysis
  - Engineering, students, and human resources support are needed

This research [or, A portion of this research] used resources at the High Flux Isotope Reactor [and/or Spallation Neutron Source, as appropriate], a DOE Office of Science User Facility operated by the Oak Ridge National Laboratory.

NNBAR collaborators near the LBP in Lund

New high-sensitivity searches for neutrons converting into antineutrons and/or sterile neutrons at the European Spallation Source

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[ESS HIBEAM/NNBAR program white-paper]

Backup Slides

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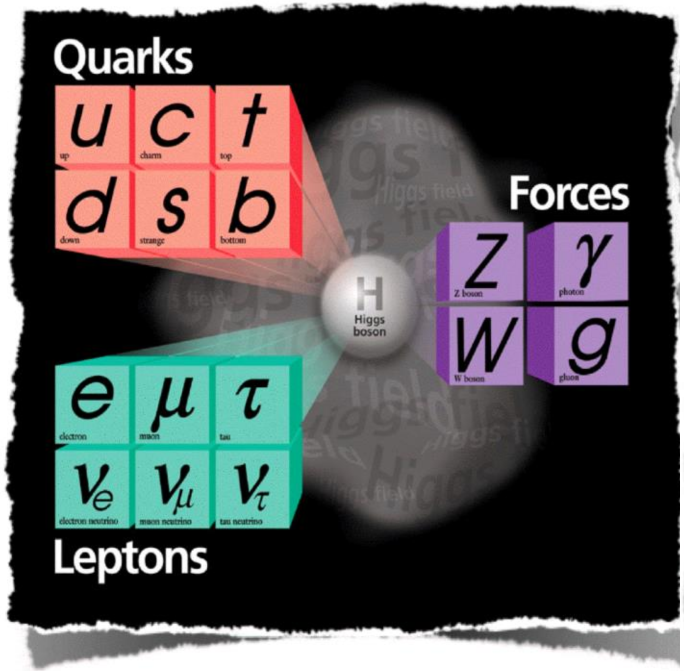

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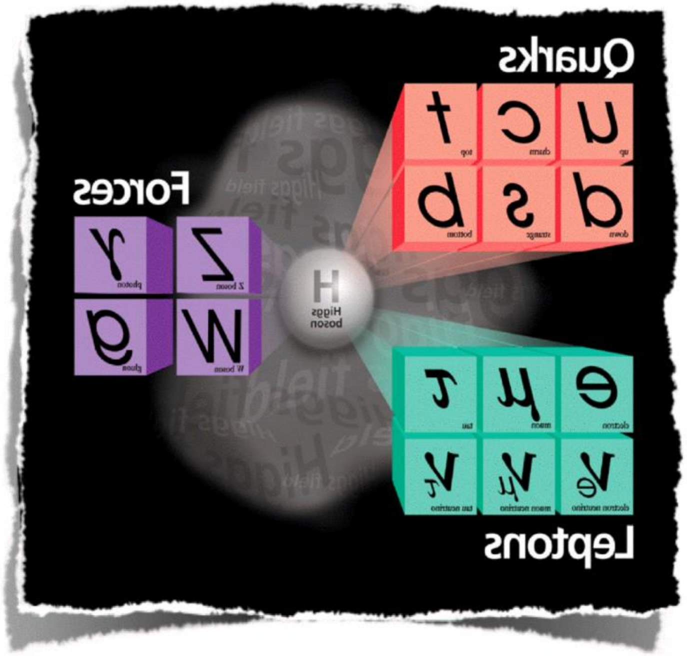

Concept of Mirror Matter

- Identical copy of SM with opposite parity
- ~No new parameters
  - Z_2 symmetry
- Long considered a ‘hidden sector’ DM candidate

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}'_{SM}$$

Phys. Usp. **50** 380 (2007)

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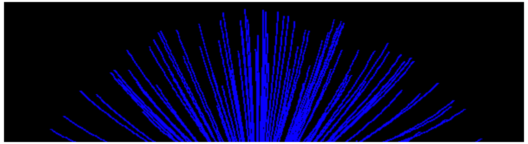
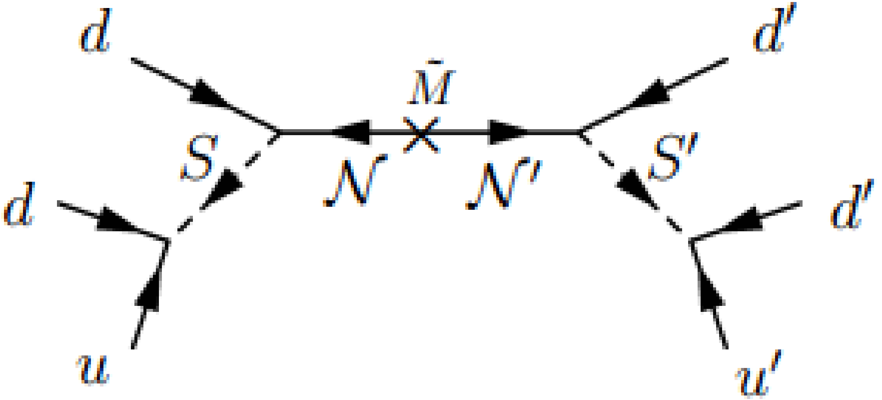
Neutral Particle Oscillations Between Sectors



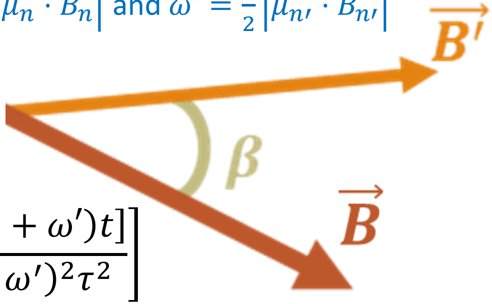
- The most interesting interaction terms in $\mathcal{L}_{mix}$ are where neutral particles (elementary, *and composite*) can mix with their mass degenerate, sterile twins
  - Under proper conditions:
    - Matter disappearance (or appearance) phenomena
    - Could be observed in the lab
- Assume that a neutral particle, such as a *neutron*, is a two component object which can oscillate:



$$\Psi = \begin{pmatrix} n \\ n' \end{pmatrix}$$

$$\mathcal{H}_{n\to n'} = \begin{pmatrix} m_n - \overrightarrow{\mu_n}\cdot\vec{B} - \frac{i\lambda}{2} & \varepsilon \\ \varepsilon & m_{n'} - \overrightarrow{\mu_{n'}}\cdot\overrightarrow{B'} - \frac{i\lambda'}{2} \end{pmatrix}$$

$\omega = \frac{1}{2}\left|\overrightarrow{\mu_n}\cdot\overrightarrow{B_n}\right|$ and $\omega' = \frac{1}{2}\left|\overrightarrow{\mu_{n'}}\cdot\overrightarrow{B_{n'}}\right|$

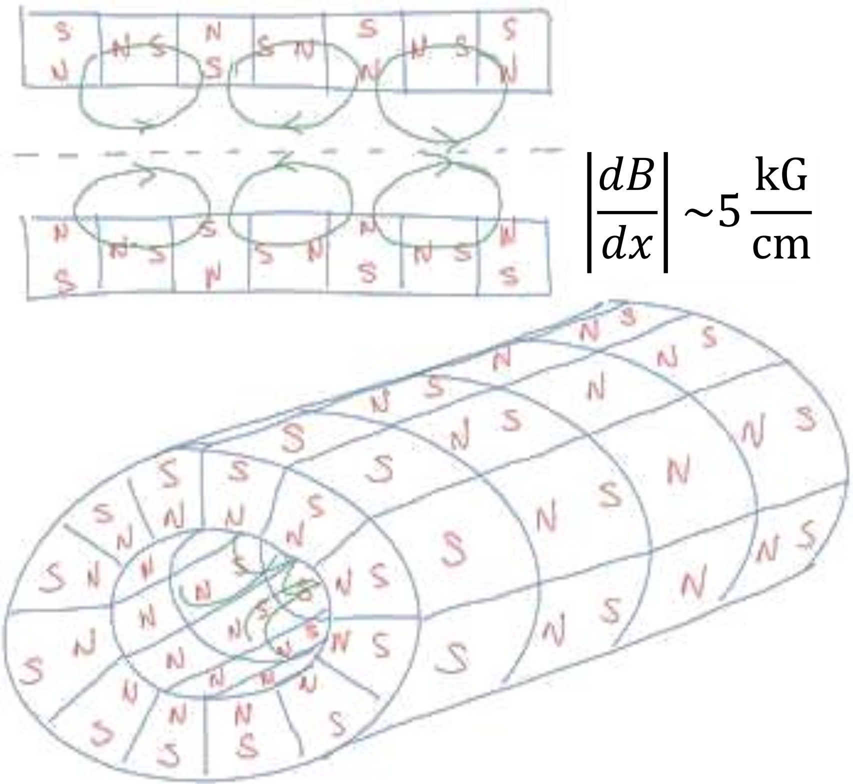


$$P_{n\to n'}(t) = \frac{\sin^2[(\omega-\omega')t]}{2(\omega-\omega')^2\tau^2} + \frac{\sin^2[(\omega+\omega')t]}{2(\omega+\omega')^2\tau^2} + \cos\beta\cdot\left[\frac{\sin^2[(\omega-\omega')t]}{2(\omega-\omega')^2\tau^2} - \frac{\sin^2[(\omega+\omega')t]}{2(\omega+\omega')^2\tau^2}\right]$$

Constraining this Physics Offers Exciting Possibilities to Understand DM and the n Lifetime Puzzle

- DM remains a central problem in physics and cosmology
  - Axions? Supersymmetry? No experimental (laboratory) evidence so far???
    - Cosmic Visions 2017 Community Report
  - **Hidden/mirror sectors** or branes? Mirror neutrons? **MM as DM**?
    - Zurab Berezhiani (ZB) 2001, ZB 2005, ZB 2006, ZB 2009, ZB 2012, Foot 2014, Sarrazin 2016, ZB 2017, ZB 2017, Broussard 2017, ZB 2018, Sarrazin 2018, Broussard 2019, Stasser 2020…
  - **Co-baryogenesis** between OM and DM sectors?
    - ZB 2006, ZB 2016, Bringmann 2018, ZB 2018
- **Losses and anomalies** with neutron traps
  - Serebrov 2008 and 2009, Altarev 2009, ZB 2012, Pokotilovski 2017, Mohanmurthy 2018
- The possible **connections to the n lifetime puzzle and V_{ud}** has given incentive to and generated a large new swath of theory
  - ZB 2018, Fornal 2018, Sun 2018, Tang 2018, Serebrov 2018
- The field has been growing and offers opportunities for a rich experimental program across fundamental particle physics
- **Utilizing cold neutrons at ORNL and ESS offers a great portal onto these fundamental searches**

④a HFIR/ANNI TMM search(es)



$$\left|\frac{dB}{dx}\right| \sim 5\,\frac{\text{kG}}{\text{cm}}$$

Adapted from Chris Crawford

$$\mathcal{H} = \begin{pmatrix} T + \mu B & \eta\mu B \\ \eta\mu B & T' \end{pmatrix}$$

$$\Rightarrow P_{n'}(t) = (2\eta)^2 \cdot sin^2\left(\frac{\mu B}{2}t\right)$$

- Break coherence of $\{n, n'\}$ oscillating system through a magnetic field gradient

$$\Rightarrow P_{n'} \cong \frac{2\eta^2}{\mu^2} \sim \text{constant!}$$

- A cylindrical Halbach array for large magnetic field gradients using permanent magnets could be used for either thermal or UC neutrons

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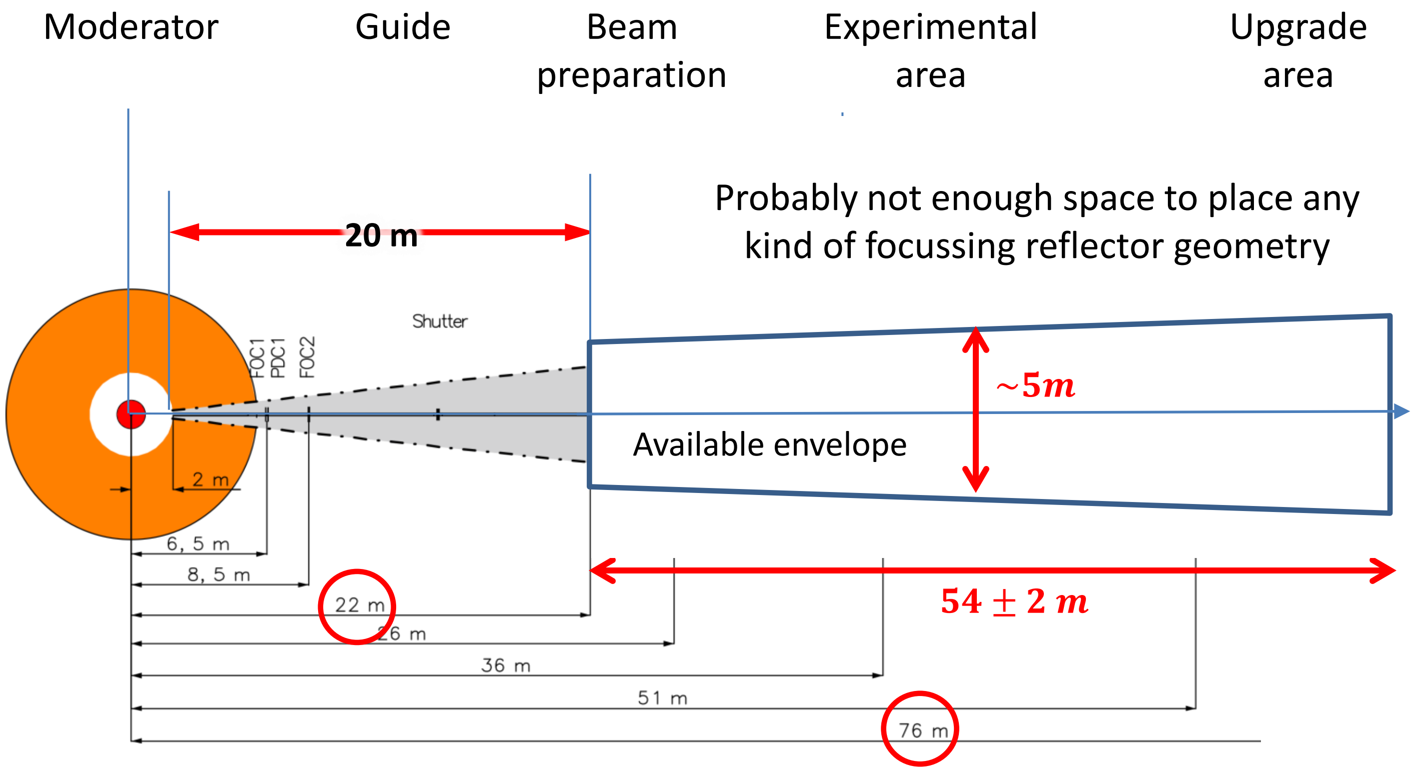
Needed Space for $n \rightarrow n'$ Search at ANNI Beamline



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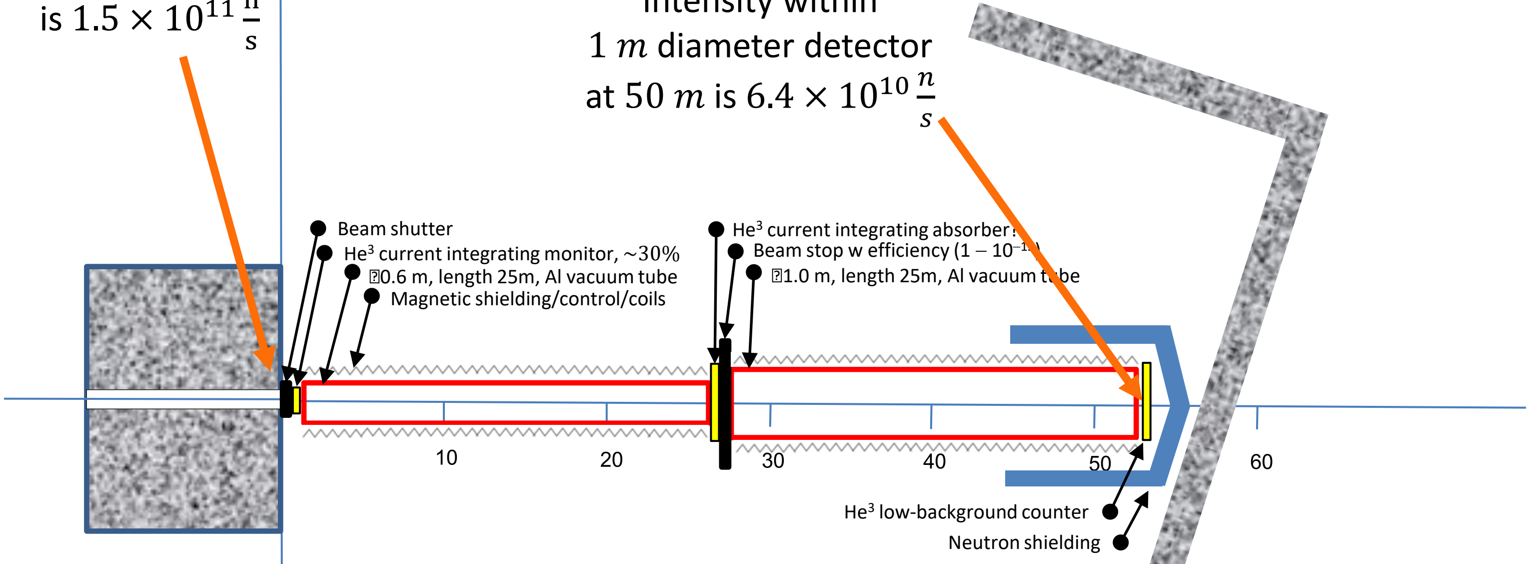
All figures assume $1MW$ operating power

Intensity within $\sim 11 \times 7\ cm$ exit is $1.5 \times 10^{11}\ \frac{\text{n}}{\text{s}}$

Intensity within $1\ m$ diameter detector at $50\ m$ is $6.4 \times 10^{10}\ \frac{n}{s}$



~22m

Basic schematic of *regenerative neutron oscillation* searches at the ANNI beam line

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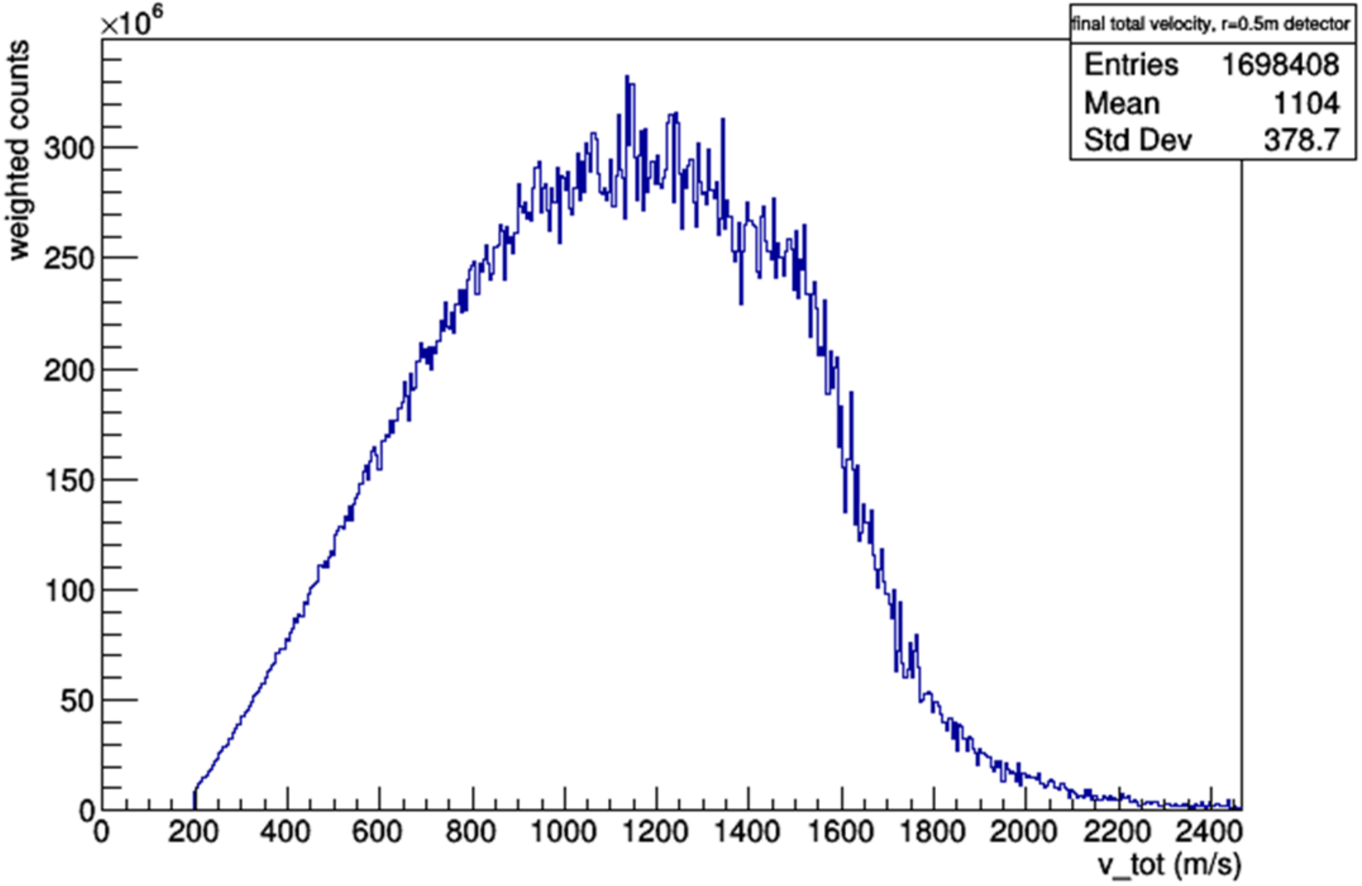
Final Velocity of Neutrons on $1m$ Detector at $50m$

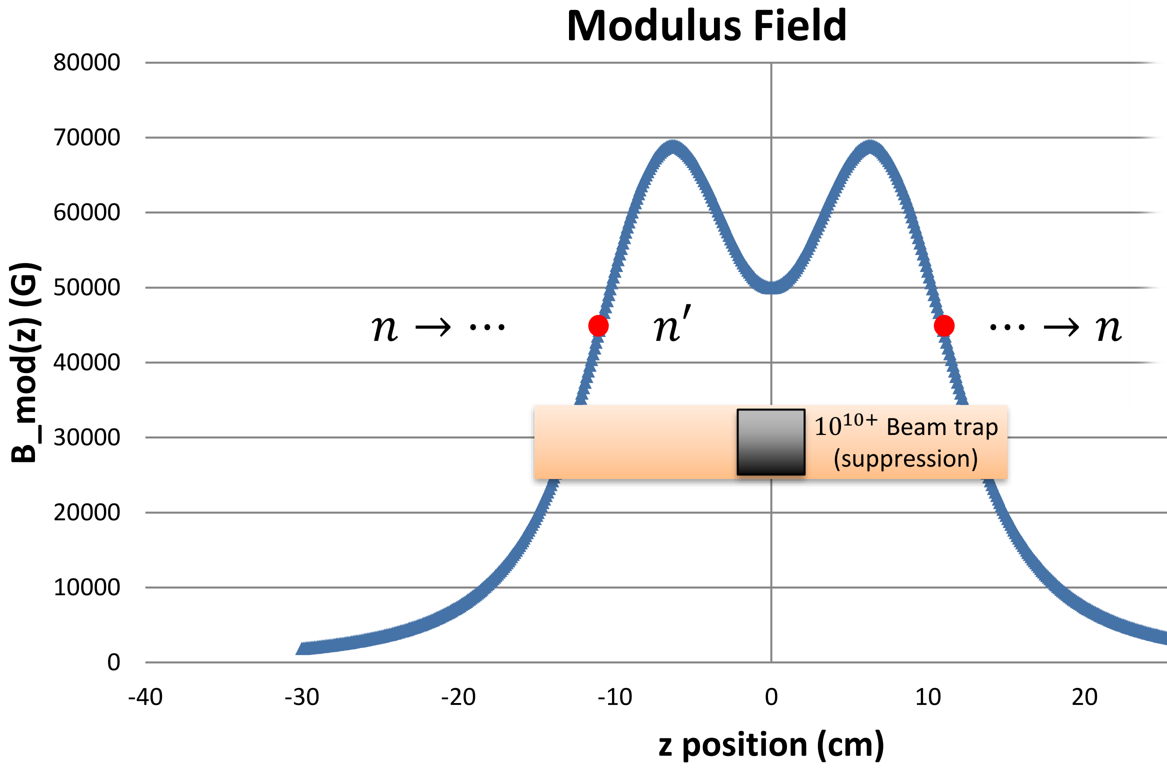


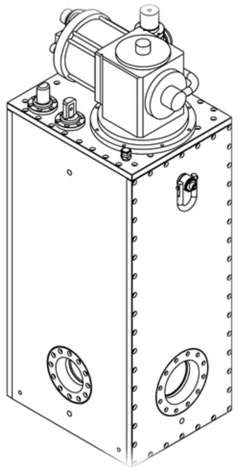
A Vision for a $n \to n'$ Search Program (at ORNL and ESS)

1. **HFIR** high-$\vec{B}$ (δm) search (ZB 2018)
   - First (SNS) run complete, analysis underway; HFIR to follow in September
2. **HFIR** high-$\vec{B}$ gradient TMM search? (ZB 2019)
3. **HFIR** $n \to n' \to \bar{n}$ search (ZB 2018, 2020)
4. **ANNI** TMM searches with gradients and gases
5. **ANNI** low-$\vec{B}$ resonant *regeneration* ($n \to n' \to n$) search (ZB 2017, Broussard 2017, Broussard 2019)
6. **ANNI** low-$\vec{B}$ resonant *disappearance* ($n \to n'$) search (ZB 2009)
7. **ANNI** $n \to n' \to \bar{n}$ search (ZB 2018, 2020)

Given enough effort, many of these could be completed on a multi-year timescale at ORNL, and then tested with a high-brightness pulsed beam at the ESS after 2025

① & ② ORNL SNS/HFIR high-$\vec{B}$ δm and gradient TMM search

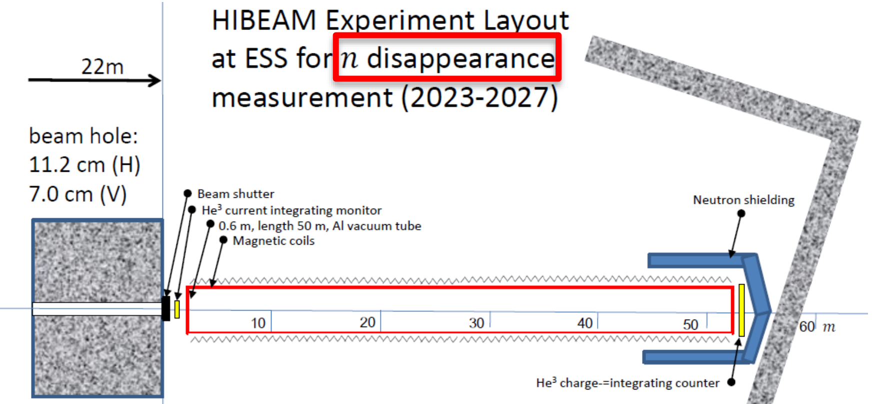


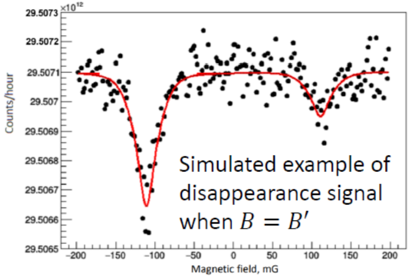


Similar future higher sensitivity searches at ESS ANNI/HIBEAM

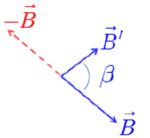
HIBEAM Experiment Layout at ESS for n disappearance measurement (2023-2027)

beam hole:
11.2 cm (H)
7.0 cm (V)





intensity through dia 1 m
@ 54 m is 6.4E+10 n/s
ESS @ 1 MW

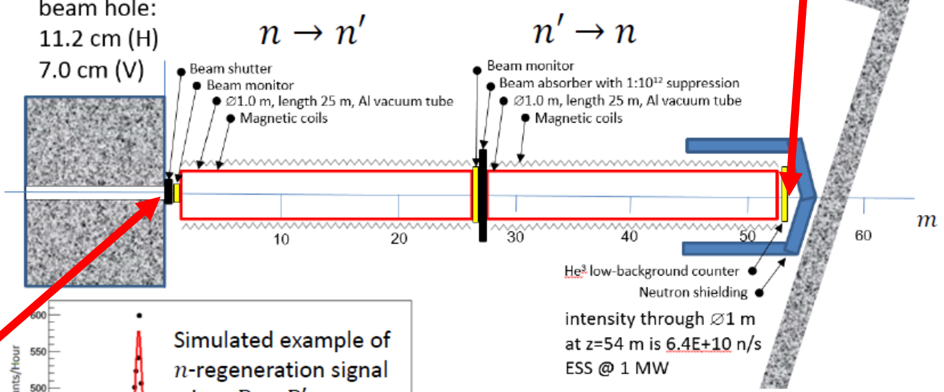


Intensity within $\sim 11 \times 7\ cm$ exit is $\mathbf{1.5 \times 10^{11}\ \frac{n}{s}}$

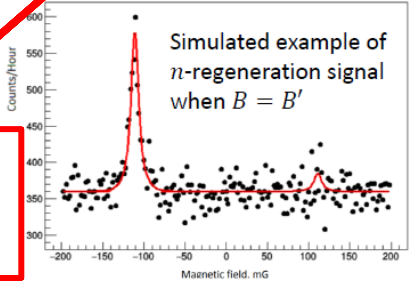
HIBEAM Experiment Layout at ESS for n-regeneration measurement 2023-2027

Intensity within $1\ m$ diameter detector at $50\ m$ is $\mathbf{6.4 \times 10^{10}\ \frac{n}{s}}$

beam hole:
11.2 cm (H)
7.0 cm (V)



intensity through Ø1 m
at z=54 m is 6.4E+10 n/s
ESS @ 1 MW



Detection of resonance via variation of magnetic field B will also demonstrate the existence of mirror photons field γ'

Adapted from T. Soldner, Y. Kamyshkov, L. Broussard

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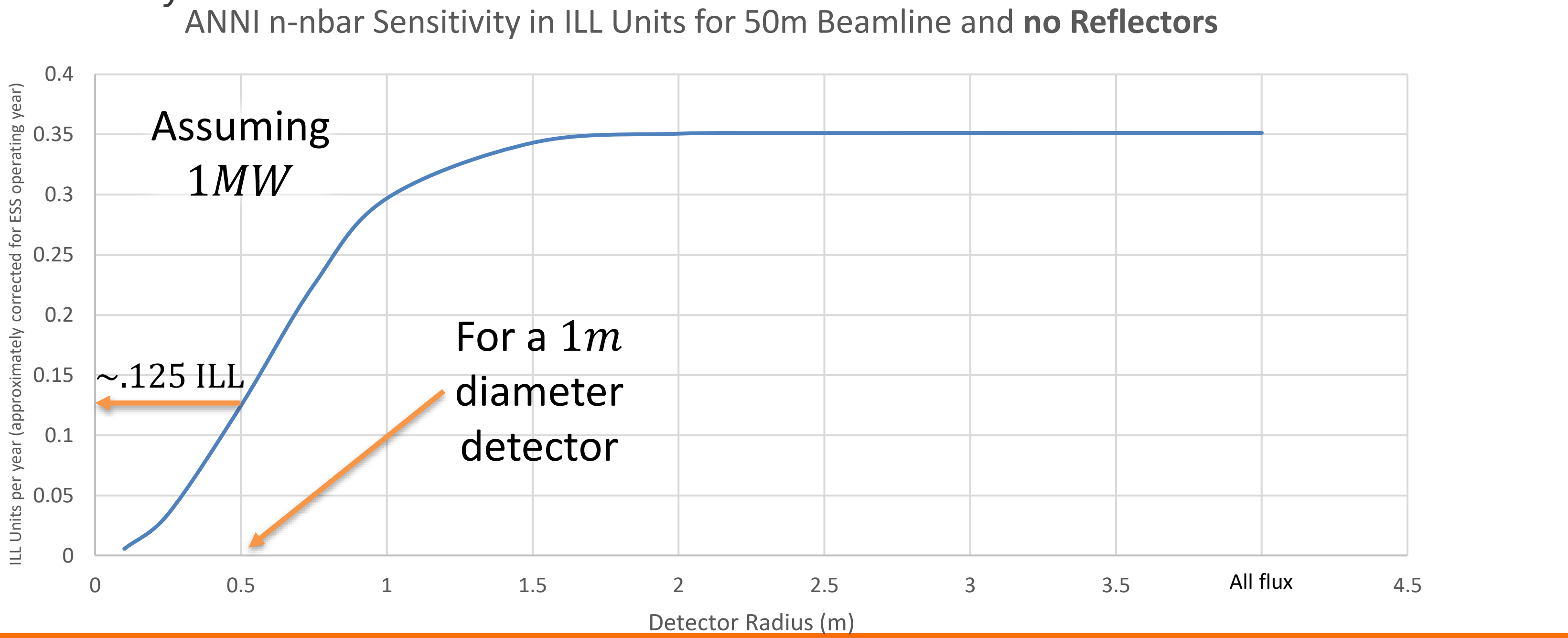
ANNI as a Test-bed for Future ESS $n \to \bar{n}$

- Our ultimate goal as a collaboration is to increase the ILL $n \to \bar{n}$ sensitivity by 10^{3+} at the Large Beamport, providing unique opportunities to study physics scales above conceivable colliders
  - Could definitively observe BNV, testing models of baryogenesis, and possibly eliminate PSB as a viable theory

ANNI can do great R&D work for LBP $n \to \bar{n}$, but also reach similar lower limits to ILL given time and n <u>reflector optimization</u>



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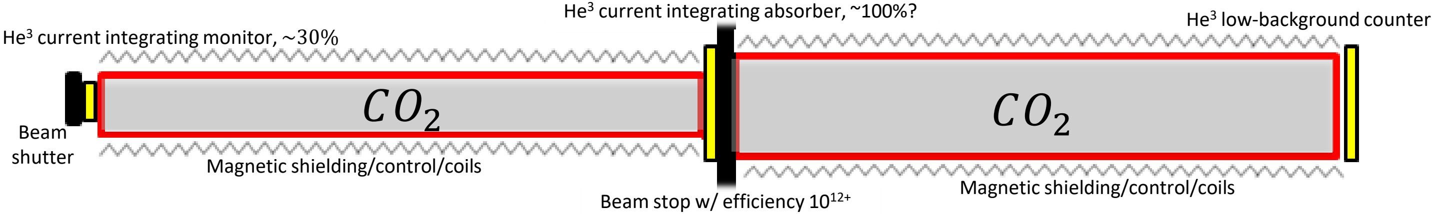
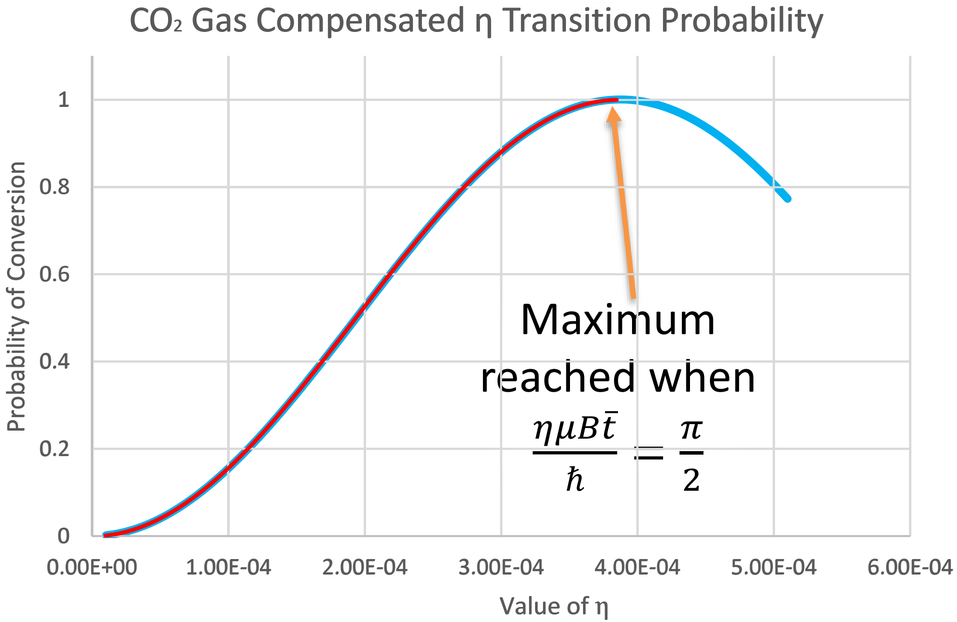
③b ANNI TMM search(es)





Add Fermi potential to compensate

$$\mathcal{H} = \begin{pmatrix} V_F - \mu B & \kappa B \\ \kappa B & 0 \end{pmatrix}$$

$$\Rightarrow P_{n'}(\bar{t}) \cong sin^2\left(\frac{\kappa B}{\hbar}\bar{t}\right)$$

Could expect large effect of $10^9 - 10^{10}$ neutron disappearances given an expecte $1MW$ flux of $6.4 \times 10^{10}\,\frac{n}{s}$ on a $1m$ diameter detector $50m$ from the guide exit

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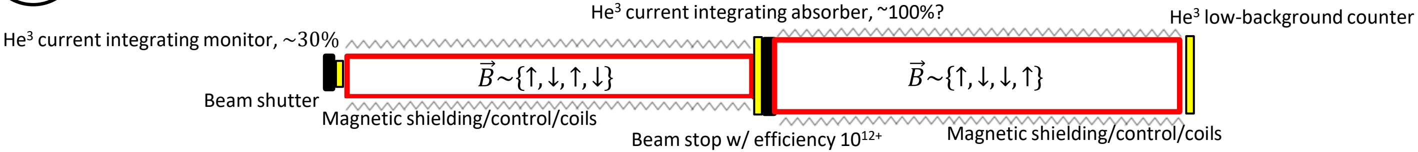
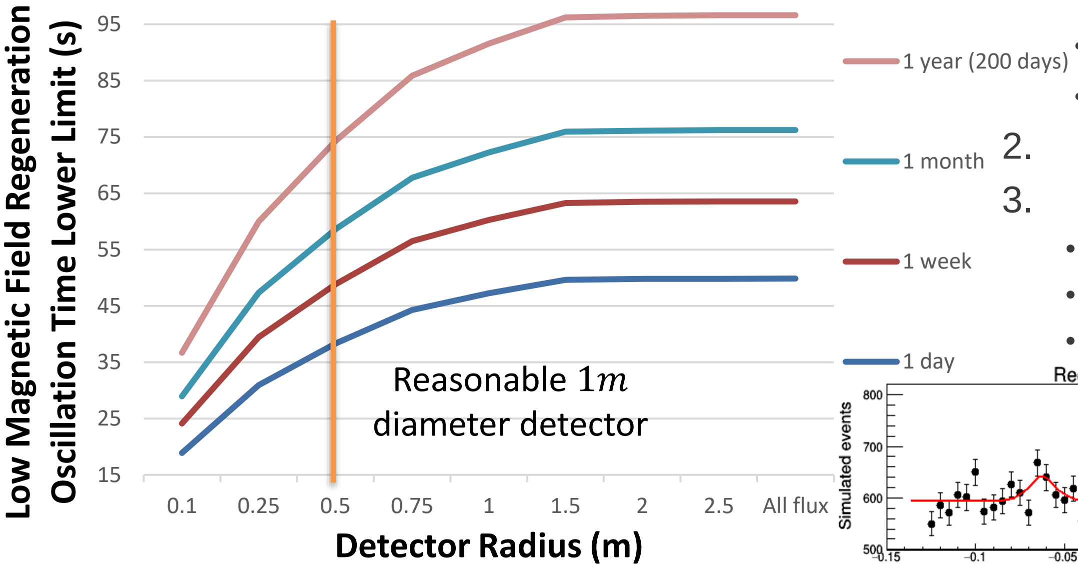
④

ANNI low-$\vec{B}$ $n \to n' \to n$ search

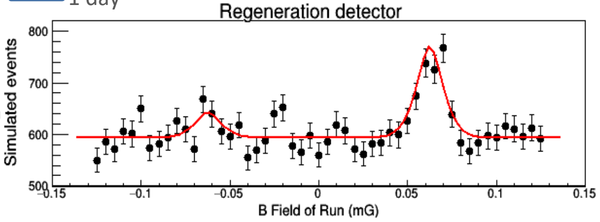


95% CL $\tau_{n\text{-}n'}$ 1MW Experimenal Lower Limits w/ 1 n/s Background Rate

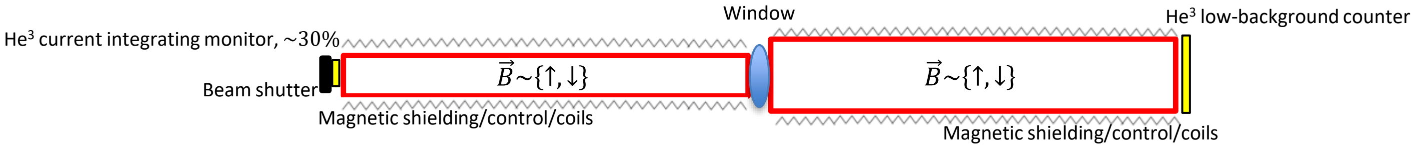


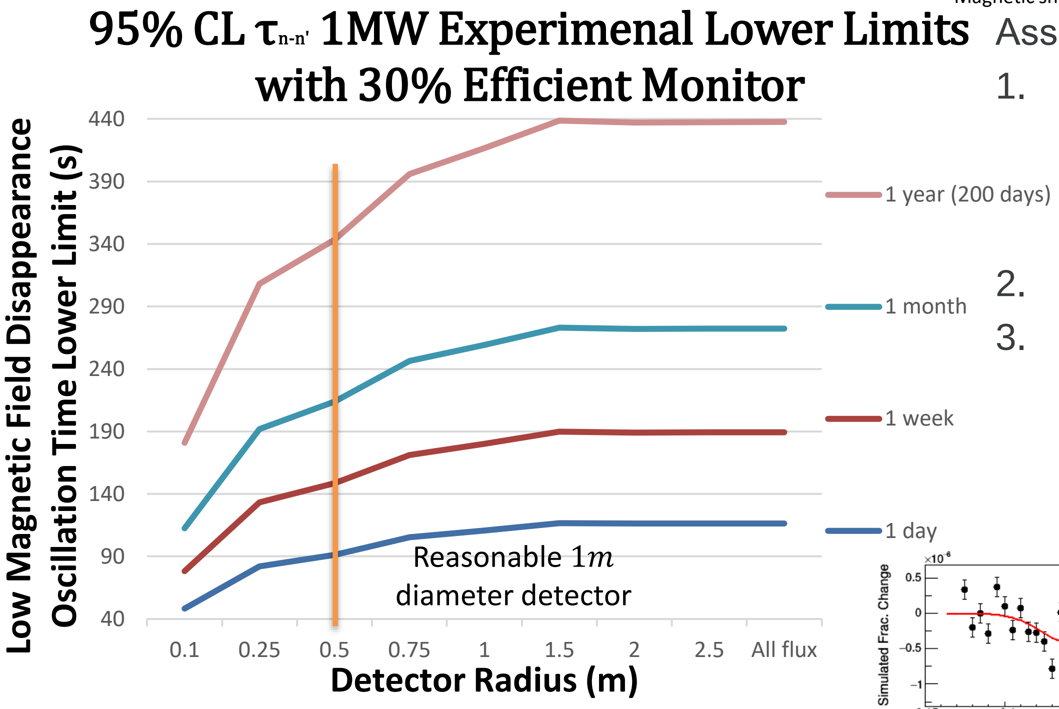
Assume…

1. Considers only flux on $1m$ target at $50m$
   - $6.4 \times 10^{10}\,\frac{n}{s}$
   - $1\ MW$ power
2. No reflectors used
3. 200 measurements
   - $(-200,200)mG$
   - $2mG$ steps
   - $\sim 2mG$ uniformity



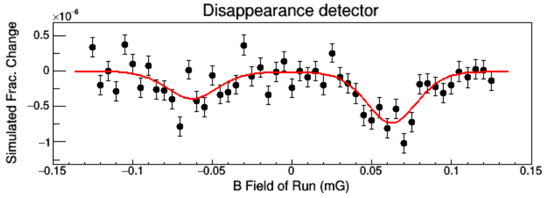
ANNI low-$\vec{B}$ resonant *disappearance* ($\epsilon_{n\to n'}$) search





Assume…

1. Considers only flux on $1m$ target at $50m$
   - $6.4\times10^{10}\,\frac{n}{s}$
   - $1\;MW$ power
2. No reflectors used
3. 225 measurements
   - 25 background runs
   - $(-200{,}200)mG$
   - $2mG$ steps
   - $\sim 2mG$ uniformity



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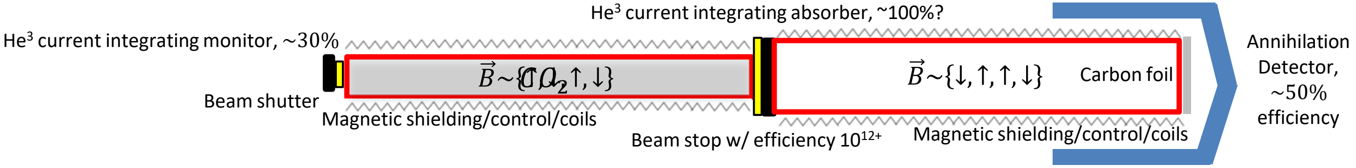
ANNI $n \to n' \to \bar{n}$ search (ZB 2018)



- Can do this **similarly to a regeneration run**
  - Simply replace last ${}^{3}_{2}He$ n-detector with a carbon foil and annihilation detector (R. Pattie and A. Young)
- Or, if measured and considered useful, use…
  - Δm conversion
  - κ conversion
    - Possibly with gas
- Check for consistency of measured oscillation times in compliance with unitarity

$$\tau_{n\to n'\to\bar{n}} = \tau_{n\to n'} + \tau_{n'\to\bar{n}} \geq \tau_{n\to n'}$$

- Such a search would be highly useful as a development platform for the ESS NNBar Collaboration and is a unique opportunity for ANNI
  - Detector research and design
  - In situ background measurements